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Moving towards deep underground mineral resources: Drivers, challenges and potential solutions

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ABSTRACT

Underground mining has historically occurred in surface and near-surface (shallow) mineral deposits. While no universal definition of deep underground mining exists, humanity's need for non-renewable natural resources has inevitably pushed the boundaries of possibility in terms of environmental and technological constraints. Recently, deep underground mining is being extensively developed due to the depletion of shallow mineral deposits. One of the main advantages of deep underground mining is its lower environmental footprint compared to shallow mining. In this paper, we summarise the key factors driving deep underground mining, which include an increasing need for raw materials, exhaustion of shallow mineral deposits, and increasing environmental scrutiny. We examine the challenges associated with deep underground mining, mainly the: environmental, financial, geological, and geotechnical aspects. Furthermore, we explore solutions provided by recent advances in science and technology, such as the integration of mineral processing and mining, and the digital and technological revolution. We further examine the role of legacy data in its ability to bridge current and future practices in the context of deep underground mining.

1. Introduction

Historically, mining mainly focused on prospecting, exploring and exploiting surface and near-surface (shallow) mineral deposits, which have become hard to find, exhausted and/or are undesirable for extraction due to limited geological confidence, socio-environmental concerns, geotechnical issues, and/or economic feasibility challenges. The mining industry is continuously challenged by resource exhaustion and environmental concerns, while adapting to fulfill the supply of raw materials within the intricate supply and demand, and socio-environmental system (Prno and Slocombe, 2012; Meesters et al., 2021). Currently, underground mining contributes ca. 12–17% (ca. 850 Mt), whereas surface mining accounts for >80% of global metal ore production (Atlas Copco, 2017; Martino et al., 2021). Underground mining also produces the least amount of waste per annum (ca. 85 Mt; overall production) compared to that of open pit mining (ca. 10,325 Mt; Atlas Copco, 2017). The potential for deeper mineral deposits continues to entice the international mining community. Societal needs, sustainability and continued economic development are the key factors motivating for the prospecting, exploration and exploitation of deep mineral deposits. Additionally, whereby long-lasting environmental impacts have been noted with the exploitation of shallow mineral deposits, deep underground mines could see a reduction of such impacts (Allenby, 1998; Sahu et al., 2015).

To date, there is no strict definition of what 'deep mining' is. Most definitions relate to changes in mining conditions with depth and the accompanied difficulties. Efforts to categorise deep mining by depth have been met with mixed success, as rock stress-related mining

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problems depend on both depth and thermal constraints combined with bulk rock properties (Wagner, 2019). A better approach from a rock-stress perspective is to define 'deep mines' in terms of rock-stress to rock-strength ratio. Currently, deep mining at 1000 m depth is common. Wellbore mining methods have progressively reached an all time depth of >7500 m (Gu and Li, 2003; Wagner, 2013; Walton et al., 2015; Wagner et al., 2016). Challenges associated with deep underground mining are numerous, including: excavation stability, rock-stress risk reduction, mine ventilation, underground productivity, human health impacts, human-machine interaction and smart mining. This review study examines deep mining in the context of: (a) providing a sustainable supply of raw materials, necessary for the modern economy; (b) identifying key driving factors; (c) describing the associated challenges; and (d) examining relevant and beneficial, scientific and technological innovations. We then briefly discuss possible future directions of deep underground mining.

2. Global mineral resource availability

2.1. Land-based global geological resource availability

The Earth's crust (about 2.5% of the Earth's volume) contains a diversity of rocks, each of which is composed of one or more minerals and glasses. In order to prospect, explore and exploit mineral deposits, it is important to understand the process(es) that are responsible for their formation. In a simplified form, mineral deposits can be classified according to their inferred formation processes, namely: (a) endogenic processes that are invariably associated with thermal and/or pressure processes, related to tectonic and magmatic events, triggered and controlled by plate movements; and (b) exogenic processes that are formed by surficial processes, e.g., weathering or shallow marine sedimentation (Marakushev, 1978; Robb, 2005). The Earth is endowed with raw materials in the form of mineral resources. However, most raw materials, such as gold, occur as finely dispersed nanoparticles in the Earth's crust and require a fortuitous combination of geological processes to concentrate into mineral deposits. Based on the latest estimates, there are ca. 45 billion metric tons of gold in the Earth's crust, of which about 244,000 metric tonnes occur as mineral deposits, while a total of 87,000 metric tonnes have already been mined (U.S. Geological Survey, 2021). The same pattern holds true for other minerals, e.g., there is an estimated 6.3 billion metric tonnes of copper resources, of which the total amount of discovered copper is ca. 2.8 billion metric tonnes and 700 million metric tonnes of copper have been produced internationally (U.S. Geological Survey, 2021). The geological processes responsible for concentrating metals into mineral deposits occur at a very slow rate compared to the rate of mining; i.e., 10^6 to 10^9 times slower than the rate of mining. Furthermore, deposit-forming processes are energy-driven, disequilibrium processes that differentially endowed some regions more than others, e.g., ca. 65% of the copper that has been discovered is found in just five countries: Chile, Australia, Peru, Mexico and the United States (Valenta et al., 2019; U.S. Geological Survey, 2021).

2.2. Driving factors and needs to move towards deep underground mining

Due to the long history of mining, shallow mineral deposits are nearly depleted, leaving the remainder of mineral resources deeper in the Earth's crust (Litvinenko, 2020). There are several main drivers that motivate the extraction of subsurface mineral deposits that include:

a) Population growth and improvements in the standard of living. The current world population is at ca. 8 billion people as of 2022, according to the most recent United Nations estimates (Worldometers, 2022). To maintain our standard of living, each person requires 15 to 20 metric tonnes of minerals each year, excluding petroleum and natural gas-related products (Minerals Education Coalition, 2021).
b) Decreasing deposit grades. For instance, in the year 1900 the average grade of economically viable copper was approximately 4%, while currently, the grades are close to 0.5% Cu, with some cases reaching 0.26% (Mudd, 2009; Toro et al., 2020).
c) Scientific and technological pursuit. The quest for scientific discoveries and technological advancements calls for exploration and extraction of raw material (Sánchez and Hartlieb, 2020). This process also creates opportunities for scientists to study geohazards, such as seismicity and geological structures ahead of mining. Deep mining revealed the existence of sulphate-reducing microbes from some of the oldest-known water on Earth (Lollar et al., 2019).
d) Socio-economic development. Metals are critical for all socio-economic and technological developments (Nelsen et al., 2010). Emerging technologies have created a preferential demand for metals such as In, Co, Li, Al, Sn, Ag, Pt and Pd, some of which are mainly found at depths of >1 km below surface (Graedel, 2011; Alonso et al., 2012; Elshkaki and Graedel, 2013; Hoenderdaal et al., 2013; Peiró et al., 2013; Moreau et al., 2019).
e) Infrastructure, industrialisation and energy supply. There is an insatiable global appetite for industrialisation and infrastructure development (Moser and Feiel, 2019). Mining has helped to shape many countries to a greater extent than any other industry (Carvalho, 2017). The green energy transition, for example, requires elements such as Co, V and Li.
f) Geopolitics and supply chain stability. There is an increasing global recognition since the 2010 rare earth elements embargo (e.g., Overland, 2019 and references therein) and heightened by the COVID-19 pandemic, the war in Ukraine and the current economic recovery, of the role of the supply and demand system in geopolitics and the sustainability of modern standards of living. This led to the creation of CRM lists, which are materials without reasonable subsitutes that societies depend on. Various countries have established CRM lists and similar strategic mineral lists (e.g., European Union Commission, 2011, 2014, 2017 and 2020; Humphries, 2019; Natural Resources Canada, 2021).

3. Current state of deep underground mining

3.1. Global evidence and trends in moving towards deep underground mining

Underground mining refers to various subsurface mining techniques used to excavate minerals (Diogo, 2020). A primary constraint of underground mining is to maximise ore extraction and recovery while minimising waste extraction. Underground mining is practical when the rock mass is suitable to be excavated profitably and has a lower ground footprint than surface mining. South Africa has some of the world's deepest mines, which serve as classic examples of supported mining methods (see section 4.2). Within South Africa, eight out of the ten deepest mines in the world are located in the Witwatersrand Basin, which is famous for its gold endowment (Frimmel, 2019, Table 1). Underground mining trends are influenced by several factors such as financial returns, perceived risks, geological, geotechnical and time constraints. Automation is also a factor aiming to extract more tonnages at a lower operating cost (Tubis et al., 2020). The push for additional automation is in part hastened by labour unrest, safety concerns and increasing global competition. The move towards deep underground mining is unavoidable and already in progress as resources extracted from such mines are necessary to sustain our societies, while enabling the transition towards renewable energy generation.

3.2. Challenges and opportunities in deep underground mining

Compared to near-sufrace mining, deep underground mining is associated with challenges such as high temperatures, humidity, airborne dust, rockbursts, large-scale cavings, mud rushes, rockfalls and

Table 1
The ten deepest mines in the world (Duddu, 2019).

Name	Operating Depth	Country
Mponeng Gold Mine	From 2.4 km to more than 3.9 km below surface.	South Africa
TauTona Gold Mine	From 1.85 km to 3.7 km below surface.	South Africa
Savuka Gold Mine	More than 3.6 km below surface.	South Africa
Driefontein 5 shaft Gold Mine	More than 3.4 km below surface.	South Africa
Kusasalethu Gold Mine	More than 3.276 km below surface.	South Africa
Moab Khotsong Gold Mine	From 2.60 km to 3.05 km below surface.	South Africa
South Deep Gold Mine	Down to 2.995 km below surface.	South Africa
Kidd Creek Copper and Zinc Mine	Down to 2.93 km below surface.	Canada
Great Noligwa Gold Mine	From 2.4 km to 2.6 km below surface.	South Africa
Creighton Nickel Mine	Down to 2.5 km below surface.	Canada

airblasts, mining induced seismicity, the intersection of hazardous gases (e.g., methane from the rock mass and toxic gases from blasting and diesel engines) and water. These challenges can be classified as environmental (e.g., high rock temperatures due to geothermal gradients, air quality issues due to poor ventilation) and rock mass characteristics (e.g., mining-induced seismicity; He et al., 2009). Although progresses have been made to ensure that rock temperatures are cooled to <25 °C, thanks to the advances in underground ventilation and cooling systems, the cost of ventilation and cooling accounts for 30%–40% of total electricity costs in an underground metalliferous mine (Schutte, 2014; Mochubele, 2014). Combating the increasing geothermal flux at increasing depths using active cooling is the most significant energy challenge in deep underground mines. Dust remains a concern in many underground mines despite the introduction of chemical and water agents that are used for dust suppression (Sepadi et al., 2020). This is in part due to the nature of mining (e.g., drilling and blasting, loading and transportation) and the presence of dry air. For certain commodities such as coal and gold, water inrushes, and methane and dust explosions have been reported, with their pathway and genesis in the deep earth being actively investigated (e.g., Manzi et al., 2012; Mkhabela and Manzi, 2017). This has created a limitation in the use of tunnel-boring machines (TBMs) in underground mines, whose application is already complicated by the intrinsic rock-mass heterogeneity. It is estimated that ca. 70% of TBM failure in underground mines is due to environmental and geology-related problems (Zheng et al., 2016). Xie et al. (2017) conceived a fluidised mining method of deep underground solid mineral resources based on a mining mode akin to a TBM. The idea is to attain in-situ, real-time and integrated utilisation of solid mineral resources through mining, sorting, refining, backfilling, power generation, and gasification of solid resources, therefore translating the resources into gas/fluid/solid mixtures.

A major concern is the physical characteristics of the rock mass. Where mining depths exceed 1000 m below surface, the in-situ stresses redistribute around the excavations, and they may concentrate in zones because of geological structures. Stress concentrations may result in damage to and failure of the surrounding rock mass and the collapse of the excavation (Ranjith et al., 2017). In-situ stresses can be regarded as the dominant factor in underground deformation and failure in deep mining (Qi et al., 2009; Xie, 2017). Mining-induced seismicity have led to fatalities, disturbance of production and in some cases mine closures (e.g., shaft no. 10, Driefontein Mining Complex, South Africa). Spalling or rockburst due to punctuated stress concentration impedes TBM cutting and can affect safety and tunnel support installation. Aside from environmental and geomechanical conditions, underground sorting and hoisting of ore is also a challenge. For example, various ore pass systems such as box holes in raise lines/stopes and slushers have been developed to aid manual ore sorting. However, they are located far away from hoisting shafts. Long underground rail tracks have also been built to allow transportation of ore with locomotives, but there are many cases of ore spillage and derailing of the train haulage system. Even in cases where ore is concentrated in-situ to reduce logistics cost, theft of the concentrates presents a management and financial challenge.

These challenges present opportunities to rethink underground mining. For example, companies such as Noranda Inc. (Canada), the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Council for Scientific and Industrial Research (CSIR) in South Africa have developed a variety of automated equipments, including load-haul-dump (LHD) machines, underground optical navigation systems, and an LHD remote control system, to meet the needs of underground hardrock mining automation (Wu et al., 2012). These tools are aimed at creating an opportunity to mine at deeper depths while reducing human health risks, improving labour productivity and reducing operating costs. In South Africa, CSIR has expanded research in underground robotic technology, to access reserves that were previously inaccessible (Perold, 2013). Despite the fact that some of these technologies remain academic, the ultimate goal is to have unmanned mines based on automation and remote operation (Scoble, 1995; Gu and Li, 2003; Ranjith et al., 2017).

4. Characteristics of stages in deep underground mining

4.1. Prospecting and exploration methods for deep underground mineral deposits

Mineral deposits are commonly discovered through prospecting, which is a variably scaled search for minerals with a potential for extraction. This is different than 'exploration', which refers to a local examination of a deposit (Marjoribanks, 1997). Prospecting methods include: (a) mapping surface rock exposures to gain an understanding of rock types, composition and anomalies; (b) digging shallow trenches to remove alluvium in order to expose the bedrock; and (c) sampling of sediments and other media to understand elemental background concentration. In some cases, the delineation of prospecting and exploration is unclear (Atlas Copco, 2017). The discovery of deep underground mineral deposits currently relies on traditional prospecting and exploration techniques. However, a number of recent advancements in prospecting and exploration could help discover and better delineate deep underground mineral deposits.

Exploration of mineral deposits employs geophysical, geochemical and drilling methods (Moon et al., 2006). Geophysical methods are preferred over others since they are more cost effective per unit of coverage area, primarily because the data generation requires less physical contact (Table 2). Geophysical methods leverage bulk physical and chemical property contrasts of rocks that result in measurable differences in material magnetism, density/gravity, electrical conductivity, radioactivity and acoustic velocity (Table 2). Exploitation in mineral deposits located at depth of >2.5 km have led to the development of new geophysical exploration techniques and in-tunnel imaging methods (Malehmir et al., 2021; Dias et al., 2021). In general, two or more geophysical methods are jointly employed in one survey to improve the confidence of interpretations and in addition, geophysical data are often correlated with geological data, such as outcrop maps, drill core logs and geochemical assays to assess the prefeasibility for further exploration and geological modelling. The choice of geophysical methods depends on the nature and composition of the target mineral deposit (Table 3).

Geochemical exploration utilises systematic measurements of one or more chemical properties of a region in the vicinity of a probable deposit. Geochemical methods include chemical anomaly detection, which attempts to determine the presence of desirable minerals by separating chemical signatures from the regional background. Detection of undefined geochemical anomalies requires systematic sampling and analysis

Table 2
Geophysical techniques and targets. Note: p = primary, s = secondary, m = maybe/sometimes. Modified after Moon et al. (2006) and Erkan (2008).

Method	Dependent physical property	Hydrocarbon exploration (coal, oil and gas)	Regional geologic study (>100 km^2)	Exploration and development of mineral resources	Engineering site investigations	Hydrogeological investigations	Detection of subsurface cavities	Mapping leachate and contamination plume	Location of buried metallic objects	Studying archaeological sites	Forensic investigations
Gravity	Density	p	p	s	s	s	s			s	
Magnetic	Susceptibility	p	p	p	s		m		p	p	
Seismic refraction	Elastic moduli, density	p	p	m	p	s	s				
Seismic reflection	Elastic moduli, density	p	p	m	s	s	m				
Resistivity	Resistance	m	m	p	p	p	p	p	s	p	m
Spontaneous potential	Potential differences			p	m	p	m	m	m		
Induced polarisation	Resistance, capacitance	m	m	p	m	s	m	m	m	m	m
Electromagnetic (EM)	Conductance, inductance	s	p	p	p	p	p	p	p	p	m
EM – VLF	Conductance, inductance	m	m	p	m	s	s	s	m	m	
EM – ground penetrating radar	Permittivity, conductivity			m	p	p	p	s	p	p	p
Magneto telluric	Resistivity	s	p	p	m	m					

Table 3
The main geophysical methods, description and application characteristics for deep underground mining (Moon et al., 2006; Erkan, 2008; Jetschny et al., 2011; Likkason, 2014; Wang et al., 2019).

Geophysical methods	Description and application characteristics
Magnetic surveys	Preferred where orebody to host-rock variation in magnetic properties is of interest. This method is used to discover deposits that host iron in magnetite, nickel in pentlandite, and titanium in ilmenite.
Electromagnetic surveys	Important where variations in electrical conductivity in the subsurface can be used to map geological structures and locate mineral deposits such as sulphides containing copper or lead, magnetite, pyrite, graphite, and certain manganese minerals.
Pure electrical surveys	Measures the differential flow of electricity in the subsurface in order to discover mineral deposits at shallow depths and determine the depth of overburden to bedrock. Electrical surveys have also been used successfully to locate the groundwater table.
Gravimetric surveys	Measures variations in the gravitational field caused by density variations in the subsurface. Has been used successfully to map geological structures such as faults, anticlines and salt domes that are often associated with oil-bearing formations. High-density minerals such as iron ore, pyrite and Pb–Zn mineralisation can also be mapped using gravimetric methods.
Radiometric surveys	Often used to map rock formations that contain elevated background concentrations of radionuclides such as uranium and thorium.
Seismic surveys	Records wave traversal through rocks and can detect changes in their physical properties. Often used to delineate subsurface layers, oil-bearing reservoirs, detect geological structures and mineral deposits. In-tunnel seismic imaging can be used for more detailed imaging. Reflection seismic surveys can be either 2D or 3D. Passive seismic can monitor ambient seismicity and image changes in surrounding rocks.

of elements using various sample media such as soil, bedrock, stream and lake sediment, natural waters, plant, drill core, air and drill chips. Geochemical exploration is concerned with: (a) the determination of the relative and absolute abundance of the elements of the Earth; (b) the study of the distribution and migration of the individual elements in various parts of the Earth with the objective of discovering the principles governing this distribution and migration; and (c) the application of geochemical principles and information in solving human requirements. By the scale of its application, geochemical exploration can be either regional, which uses coarser sample coverage to produce large-scale maps, e.g., planning scale of 1:10,000 to 1:2,000,000 or more (Moon et al., 2006), or local, which typically follows regional mapping to provide higher resolution maps of bed rock, weathered cap rock, soil, water and plant, often at a scale of 1:2500 to 1:10,000.

There are two types of geochemical exploration sampling which depends on the nature of target, namely: conventional and non-conventional. Conventional sampling includes lithogeochemical bedrock analysis (i.e., weathered bed rock/gossan), pedogeochemical/soil (i.e., transported overburden/talus), stream sediments, hydrogeochemical, biogeochemical and homogeochemical analyses. Sampling using media aside from conventional types is non-conventional and is preferred for areas with deeply buried deposits that are covered by transported soil, desert, sand and talus. Non-conventional methods used for subsurface mineral deposits include vapor geochemistry (i.e., sampling of atmosphere, soil and gas), electro-geochemistry (i.e., extraction of metals in receiver electrodes/electrolytes) and isotope studies. Subsurface sampling primarily makes use of exploratory drilling, which variably: (a) assesses mineralisation potential; (b) collects samples for geological, geochemical, geomechanical and petrophysical analyses and correlation; (c) allows for estimation of the boundaries and sizes of mineral resources and reserves; and (d) maps various structures (Fig. 1). Two common drilling methods include core drilling that yields a

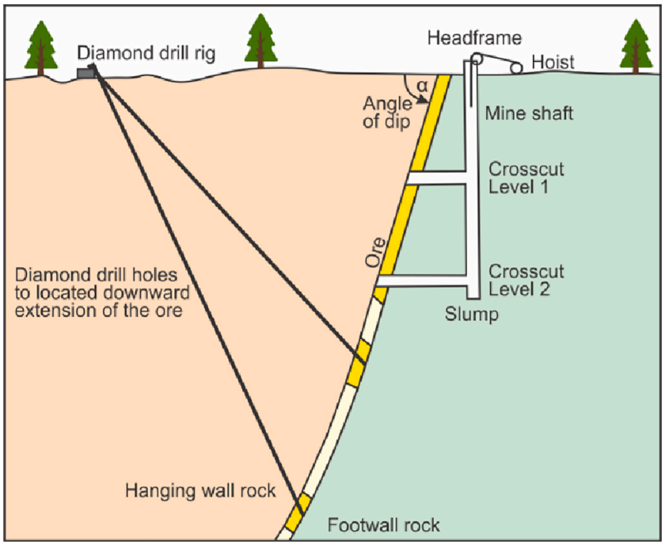

Fig. 1. Exploration for mineral deposits using diamond drilling.

cylindrical sample of the ground to a given depth, and percussion drilling that yields crushed samples that consist of cuttings from a given depth. These methods have led to the development of additional variations for exploration such as direct and reverse circulation drilling, which produces chips for grade control or ore content (Talapatra, 2020).

In addition to geological, geochemical and geophysical exploration, there is an increasing use of (spectral) remote sensing due to its cost effectiveness and non-contact nature. Since the advent of satellite imagery with the launch of the first Earth resources satellite (Landsat 1) in 1972, exploration geologists are increasingly utilizing digital images of the terrain (Moon et al., 2006). Remote sensing exploration methods use high resolution multispectral satellite and airborne digital data (Gomarasca, 2009). Remote sensing is either active or passive depending on the source of illumination. Both types of sensors record reflected, transmitted or emitted photon beams. However, passive sensors require external illumination sources, such as the sun or natural thermal radiation. Passive remote sensing is popular and its instruments include the: Landsat Multispectral Scanner (MSS); Landsat Thematic Mapper (TM), which utilises additional wavelengths, and has superior spectral and spatial resolution compared to MSS images; Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on NASA's satellite Terra; SPOT - a French commercial satellite with stereoscopic capabilities; high resolution commercial satellites, such as Ikonos (Wahl, 2004), the first of the next generation of high spatial resolution satellites, and QuickBird (Yang et al., 2006); space shuttle-based imagery; and airborne scanning systems such as drone-based systems that have even greater resolution and can record more and narrower bandwidths. Active sensors emit their own source of energy, for example, radar (microwave) and lasers (Pan and Zhang, 2020), and records the reflected energy spectrum. Application of continental-scale mineral mapping using remote sensing was recently demonstrated by *Dale Roberts* at CSIRO (2021) as part of "Exploring for the Future" project (Fig. 2), which aims to outline the mineral, energy and groundwater potential of northern Australia (CSIRO, 2021).

4.2. Deep underground mining methods, planning and optimisation

Underground mining methods have evolved from primitive hand-held hammer and chisel to modern automated and mechanised mining. As the exploitation of deep mineral deposits gains prevalence, it is reasonable that mining methods will continue to evolve. Currently, mine layouts are designed in response to the characteristics of the mineral deposit, including its size, orientation, heterogeneity, rock strength, mineral economics and geotechnical constraints (Brady and Brown, 2006; Musingwini, 2016).

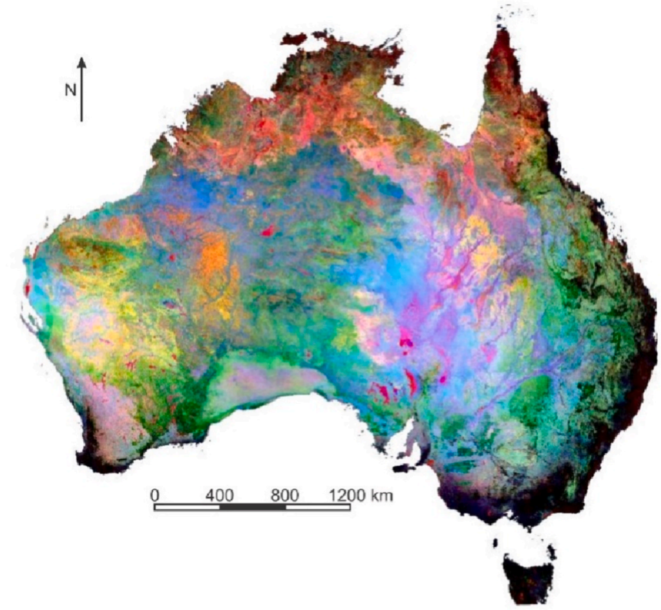

Fig. 2. A new satellite image of Australia, at continental-scale "Directed PCA" using the Sentinel-2 surface reflectance pixel composite mosaic. Each pixel is 10 m × 10 m. The red colours map clays, green colours map iron-oxides and blue colours map silica. The low albedo zones (shaded in black) are heavily vegetated zones and forests that strongly absorb photon energy and therefore prevent measurement (CSIRO, 2021).

Depending on the characteristics of the deposit and the country rocks, it is reasonable that some existing underground mining methods are adaptable to deep underground mines. Current underground mining methods can be classified into three main groups, namely: (a) naturally-supported, (b) artificially-supported, and (c) unsupported (Fig. 3; Brady and Brown, 2006). Naturally-supported mining methods leave a portion of unmined ore as pillars, commonly referred to as remnant pillars. Artificially-supported methods use filling (e.g., rock waste mixed with a low content of cement) or artificial pillars to support the roof, walls, anchors, roof bolts, etc. of a mine. Finally, unsupported mining methods do not attempt to provide long-term support to the mine. Rather, unsupported methods leave rocks to slowly succumb to local stresses, which cause an eventually in-situ filling of voids.

Naturally-supported mining methods are best used in areas of high stress in a particular direction. In the deep mining environment, high stresses may occasionally result in rockbursts. For this reason, sequence of extraction and orientation of the pillar are of critical importance (Brady and Brown, 2006). Naturally-supported mining methods can be divided into (Fig. 3):

a) Room and pillar: as the ore is extracted, portions of the ore are left unmined, leaving support pillars. Applicable to structurally strong ore deposits that are tabular-shaped.
b) Sublevel and long-hole open stoping: both the orebody and wall rocks are unsupported, while the support is provided by the country rocks, which are developed as pillars. Applicable to massive or steeply dipping stratiform orebodies.

Artificially-supported mining methods are often used in mines where the country rock is weak. Such methods are employed to control both local and wall rock behaviours. Artificially-supported mining methods can be divided into (Fig. 3):

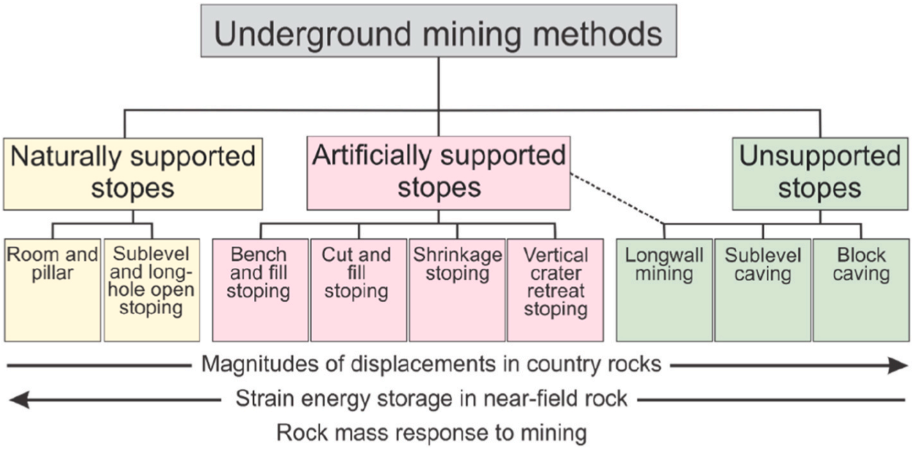

Fig. 3. Underground mining methods and their rock mass response. Figure modified from Brady and Brown (2006).

a) Bench and fill stoping: drilling and excavation drives are mined perpendicular and parallel to the orebody. The mining advances by sequential blasting along the pre-cut drives. Afterwards the stopes are backfilled to provide support.
b) Cut and fill stoping: voids are backfilled to provide support and working floor. Cut and fill can also be “descending cut and fill”, where the fill is the roof of the working chamber. Applicable to moderate to strong ore deposits with weak country rocks. The ore deposit itself is tabular to irregular-shaped, steeply dipping and of high grade.
c) Shrinkage stoping: this method is similar to cut and fill, but with ore extraction occurring in a vertical to near vertical manner. Applicable to similar orebodies described in cut and fill stoping.
d) Vertical crater retreat stoping: the method is a larger scale of shrinkage stoping made possible by recent advancements in large-diameter explosive design. Applicable to orebodies that are similar to cut and fill stoping, but where sublevel development is impossible.

Unsupported mining methods have gained prominence in current deep mines (Table 4; Brady and Brown, 2006). Unsupported mining methods such as sublevel and block caving are desirable where mining started at a shallow level, such as open pit mines that later expanded to underground. Similar to artificially supported mining methods, unsupported methods are classified into:

a) Longwall: this method is applicable to any ore strength with weak to moderate surrounding rock strength. It is chiefly used in tabular orebodies with a low or flat dip.
b) Sublevel caving: applicable to moderate to strong ore strength, but weak country rock strength. It is most commonly applied in tabular and massive orebodies that are fairly steep.
c) Block caving: this is the most preferred method for massive and thick orebodies with weak ore and surrounding rock strength. Block caving is a mining method that can achieve high extraction rates and low operational costs. Ore grade can be low to moderate and the deposits can be fairly steep (Pourrahimian and Askari Nasab, 2010; Brown, 2007).

Moreover, preconditioning of an orebody using the sublevel caving method (Fig. 3) has proved to be a reliable technique not only to improve production rates (because of a reduction of issues by using gravity flow) (Brown, 2007; Catalan et al., 2012; Castro et al., 2014; Brzovic et al., 2014), but also to reduce seismic intensity (Toper et al., 2000; Cordova et al., 2021; Fryer et al., 2019).

Table 4
Underground mining production improvements brought by unsupported mining methods.

Mine (country)	2021 production rate (metric tonnes per day)	Expansion production rate (metric tonnes per day)
El Teniente (Chile)	145,000	290,000
Salvador (Chile)	15,000	35,000
Andina (Chile)	35,000	150,000
Chuquicamata (Chile)	140,000	
Henderson (USA)	45,000	35,000
Bingham Canyon (USA)	30,000	
Philex (Philippines)	35,000	30,000
Grasberg (Indonesia)	30,000	160,000
Northparkes (Australia)	50,000	20,000
Argyle (Australia)	80,000	
Palabora (South Africa)	20,000	30,000
Cullinan (South Africa)	30,000	30,000
Finsch (South Africa)	15,000	17,000
Kimberley (South Africa)	17,000	6000
Venetia (South Africa)	250,000	
Jwaneng (Botswana)	10,000	
Orapa (Botswana)	20,000	
Kiruna mine (Sweden)	66,000	

Once a mining method has been selected, protocols for mine planning and scheduling are developed (Fig. 4) (O’Sullivan and Newman, 2015). There are four main levels of underground mine planning, that is: (a) scenario planning, which focuses on the long term (e.g., decadal) and is mainly for positioning the company in terms of markets, supply/demand, competitiveness; (b) the strategic level, which is a high-level plan that focuses on achieving a financial objective (e.g., the Net Present Value [NPV]) for medium to long term strategies such as growth through acquisition; exploration, organic growth; (c) the tactical level, which is concerned with infrastructure deployment, production level, cost and efficiency control to maximise the fulfilment of the strategic goal; and (d) operations or budget level for operational efficiency (Tholana et al., 2013; Nwaila et al., 2021). The level of planning detail generally increases from the strategic to operational level.

Top-down, bottom-up and dual or hybrid approaches are all possible for mine planning. The top-down approach informs successive levels of detail of the directing context. The bottom-up approach builds up from a short-term base into longer term consolidation. The dual or hybrid

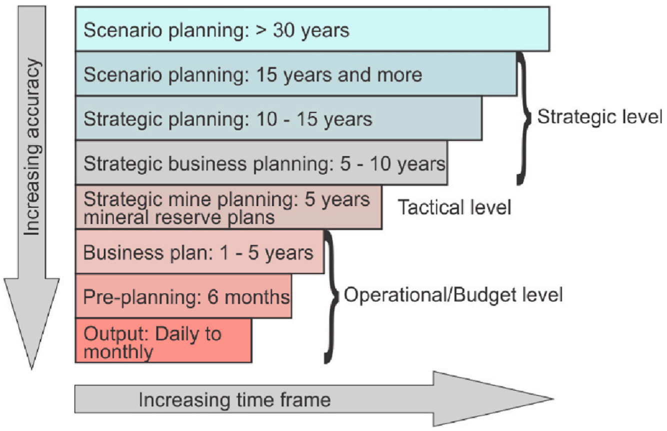

Fig. 4. Stages of mine planning at a strategic, tactical and operational level versus accuracy.

approach uses top-down goals to inform planning at lower levels, while simultaneously, plans are produced using dynamic feedback from the bottom-up to ensure that they are realistic. An important component of successful mining of underground mineral deposits is mine plan optimisation. Optimisation seeks ideal values for key variables that are contained within an objective function (e.g., grade mix and planning optimisation, cut-off grades, cost/volume analysis, marginal mining to fill capacity, profit margin and NPV), subject to a set of constraints on the values of the controlling variables (Nwaila et al., 2021). The constraints are typically realities of environment and operation and can include orebody characteristics, extraction capabilities, market conditions and financial state of the company. Optimisation is typically achieved through an iterative process, decision tree analysis, stochastic methods, multi-linear programming and option pricing.

Deep mining has the potential to increase the life of a mine, reduce waste and create stability in production of precious and base metal ores. However, new technologies for rock cutting and breaking are likely necessary to sustain autonomous production and enable faster, more cost-efficient delivery systems that are vital to deeper underground mines. Adoption of such technologies would increase project NPV by extracting new orebodies faster, increasing the production rate, and improving product value, and thus overcoming the depth-associated challenges of material backfill and delivery of operating supplies (Nehring et al., 2012; Jory et al., 2016; Musingwini, 2016).

4.3. *Extractive technologies for deep underground minerals resources*

There are ongoing pressures to reduce the mining footprint, particularly on the surface. One promising solution is the further integration of underground mining and mineral processing. Mineral processing usually occurs above ground, although numerous underground crushing and screening facilities exist. More integrated examples also exist, such as the McArthur River uranium mine in Saskatchewan (Canada) that uses underground semi-autogenous grinding with hydraulic transport to a surface processing facility; and the Codelco's Andina copper mine in Chile, where the mineral processing plant (grinding and flotation plant treating 32,000 tons per day) is underground because of the extreme surface climatic conditions (Brewis, 1995; Grigg and Delemontex, 2015).

The oldest underground gravity-recovered gold processing plant was owned by Welsh Gold PLC at their Gwynfynydd gold mine in north Wales (United Kingdom), which operated between 1991 and 1999 (Devereux and Gray, 1996). At that time, the road header technology limited the extent of underground mineral processing. Currently, underground processing is practical and its benefits (e.g., favourable economics and ease of backfill) can be easily realised. Gekko Systems (Gekko) is an Australian company that has developed the Python underground processing plant (UPP) for deposits that are amenable to gravity recovery with or without flotation. The UPP is designed to operate in a 5 m × 5 m tunnel, to produce high-grade concentrate that is pumped to the surface (Gray and Hughes, 2007; Grigg and Delemontex, 2015). The UPP uses a control system typical of Gekko's other modular processing systems (Automation.com, 2017; Rockwell Automation Inc., 2017). Since the UPP concept was conceived by Gekko in 2008, there has been a reluctance to seriously consider and conduct the appropriate due diligence required to implement an UPP-type of plant into an underground operation. Main design options and characteristics of underground mineral processing are presented in Table 5. A more conservative underground mineral processing facility would pre-concentrate the ore in order to reduce the amount of material transported to surface, thus leaving a significant portion of the waste behind for backfill (Morin et al., 2004). As presented in Table 5, while the reduced transport costs are clearly an incentive, there are constraints upon the construction and operation of an underground processing plant.

Retrofitting underground mineral processing plant into existing mines would strongly depend on the characteristics of the mine, the ore and the mineral processing plant. The processing plant could be integrated into the mining architecture, either as a pre-concentration or fullmill operation. One approach (Fig. 5) requires that several stopes are routinely operational to meet production targets, with several old stope voids available for backfilling. The stopes below the level of the plant supply a stream of fragmented ore via drifts and ramp access. Stopes at or above the level of the plant can take advantage of gravity and supply ore via drifts and ore passes. The main means of handling the concentrate from milling is via a drift and vertical shaft. An alternate means is via secondary transport to surface, the ramp system. The ramp also provides backup to the mill for transporting waste reject from the processing to surface in the event that adequate stope void space is unavailable or other factors impede waste disposal. Gravity affects the management of waste reject as with the ore feed to the mill plant. Drifts, raises and ramps can be optional in this design to transport and place the waste as backfill. Such systems are dependent on the reliability of the backfilling process. The secondary transport of waste to surface would be important in order to maintain production continuity. This system is waste-management bound. The swell of rock on fragmentation implies that some waste must be transported to the surface.

5. Relevant scientific and technological innovations significant to deep underground mining

5.1. *Modern technologies and scientific developments*

In deep underground mines, hazards may be more frequent (e.g., seismic events, rockburst, rockfall, mud rush or airblast) and more impactful (e.g., loss of human life and productivity). In some cases, manual labour becomes unfeasible, for example, where the ambient temperatures are too high. The main modern development that supports deep mining is the digital and technological revolution, which provides three key ingredients: (a) sensors, (b) data and algorithms, and (c) computing power (Ghorbani et al., 2022). Together, they produce self-reinforcing, system-level positive feedback to produce ever-increasing levels of sophistication. For example, sensors generate data, which empowers alorithms that enable analytics, predictive modelling and automation, which drives the evolution of computers. More capable computers permit the use of increasing amounts and complexity of data and allows for the deployment of higher densities and varieties of sensors (Ghorbani et al., 2022). It is unsurprising that many of the ideas to evolve the mining industry are technologies enabled by the key ingredients, such as artificial intelligence, machine learning and data (Global Mining Guidelines Group, 2019). We foresee four main applications of technologies and data to deep mining: (a) digital mine integration platform,

Table 5
Main design options and characteristics of underground mineral processing (Lloyd, 1979; Lloyd, 1990; Schena et al., 1990; Brewis, 1995; Collins, 1995; Feasby and Tremblay, 1995; Parsons and Hume, 1997; McCulloch et al., 1999; Moss, 1999; Peters et al., 1999; Dyck, 2001; Klein et al., 2002; Lane et al., 2008; Grigg and Delemontex, 2015).

Options for underground mineral processing	Description and characteristics	Practical considerations for underground mineral processing
Pre-concentration	**Objectives:** • Reject waste at as coarse particle sizes as possible. • Reduce cost of backfill, transport and processing of material. For deep mines, reduction of mass transport costs is important to its financial viability. **Most probable advantages:** • Cheaper haulage and transportation, milling and mine waste management. • Improvement in ground control and conditions, and potentially reducing rockburst by using better quality and coarser backfill. • Reduction of fine waste and separation of non-reactive from reactive waste for disposal. Therefore, reduction of grinding and fine particle processing costs. • Reduction of capital and operating costs, thus lowering the cut-off grade and increasing the potential reserve and the value of ore delivered to the surface. • Reduced mining selectivity needs, and more options for bulk mining methods. **Probable advantages:** • Increased mining rate and metal production. • Delivery of smelter-grade ore to surface, thus avoiding the need for a surface concentrator plant. • Increased maximum stoping height (ground conditions permitting), allowing more productive and automated mining equipment. **Pre-requisite factors and considerations:** • **The orebody:** Characteristics of the orebody influences the desirability of the mining method. Unsupported or caving methods increase ore dilution, selective mining methods limit ore dilution, but costs more. The availability of a concentration plant impacts the selection of a suitable mining method. • **Geology:** The geology of the rock mass hosting the mineral processing plant is important in controlling the stability of excavation and need for long-term support. • **Distance of mine from concentrator:** A concentrator near the mine permits the utilisation of both conventional handling and pumping systems. At larger distances, a pipeline application is financially impractical. • **Backfill requirements:** Apart from caving methods, every mining method may require backfill. Rejects from gravity separation circuits are the preferred backfill materials, since they are chemically stable. Depending on packing density, most of mined material can be used for backfill. This is an incentive for selective mining. **Primary integration issues:** • **Pre-concentration technology:** Space-efficient technologies are preferred. Dense media separation may be prohibitive in terms of infrastructure and space requirements associated with the media recovery circuit. Other technologies include electronic sorters, magnetic and electrostatic separators. • **Material handling:** The use of pre-concentration reject (2–15 cm fragments) for backfill. The options include using reject directly, or mixing with cemented tailings at surface or underground as backfill. Other material handling issues relate to variable mining rates, underground storage for pre-concentrator surge capacity and storing concentrate and waste. • **Production rate:** Assuming a fixed rate of transport of concentrate via shafts to the surface, as orebodies becomes narrower or drop in grade, pre-concentration processing rate will need to increase. For mining, the desired production rate and pre-concentrator feed grade will dictate the extraction rate and sequence. • **Fragmentation/ Comminution:** Assuming fine particles are combined with concentrate, reducing the amount of fine particles generated during comminution will increase the amount of waste rejected during pre-concentration.	• The ability to apply pre-concentration is determined by the liberation characteristics of the ore, such as its mineralogy. • Processes include crushing, screening and coarse particle. • The physical volume of the processing facility should be as compact as possible to minimise costs. • The process should require a minimum amount of infrastructure. In general, dry processes are preferred over wet ones. • Geotechnical constraints may limit the size of excavation to house a processing facility. • The process should be robust with respect to being capable of treating ore at a range of feed rates and grades while maintaining high metal recoveries. • Processes that can separate at coarse particle sizes and requires minimum comminution, are preferred over fine-particle processing technologies. • The waste should be suitable for backfill with regards to its physical properties and volume. Returning waste to mined voids limits the amount of rock that needs to be rejected. At higher rejection ratios, waste will need to be transported to surface for storage. • Processing equipment should require a minimum amount of infrastructure. • Mobile and modular processes are preferred over centralised ones.

(*continued on next page*)

Table 5 (*continued*)

Options for underground mineral processing	Description and characteristics	Practical considerations for underground mineral processing
	Comminution should be optimised by a combination of controlled blasting and proper design of the crushing/screening facility.	
Full-scale mineral processing	This would involve crushing, grinding, mineral separation and de-watering. Integration of full-scale circuits into underground excavations would likely be preceded by success in pre-concentration efforts.	

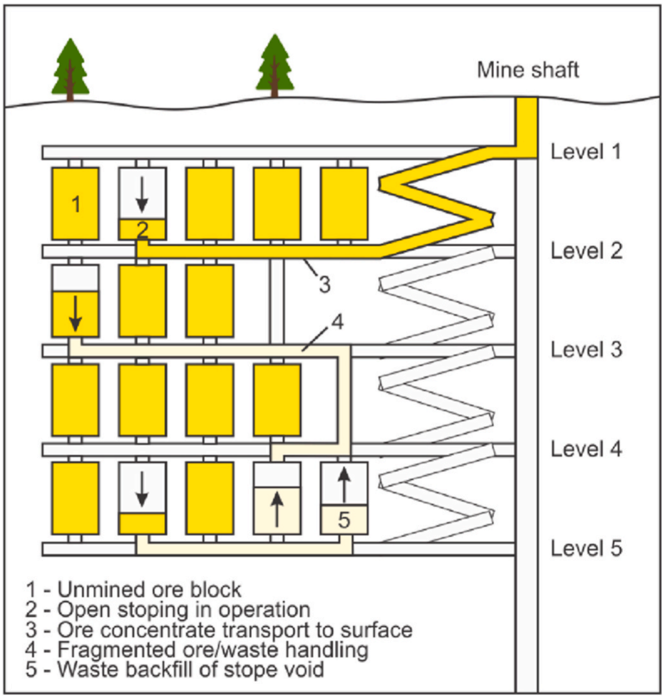

Fig. 5. Conceptual mine layout with underground processing plant (modified after Klein et al., 2003).

(b) mining simulation system (see section 5.3), (c) underground positioning and navigation technology, and (d) mining environmental intelligence perception.

For the extraction process, an objective is to automate as much of the process as possible to increase extraction efficiency and reduce human exposure to risks (Global Mining Guidelines Group, 2019). For example, automation of mechanical and repetitive processes would most likely involve technologies such as multispectral photometry, LiDAR-based distance sensing to characterise rocks and to guide autonomous navigation. For this purpose, remote sensing, in-tunnel seismic imaging, micro-seismic monitoring, pattern recognition using artificial intelligence and robotics are highly suitable to the deep mining environment.

For environmental monitoring, the goal is to use sensor networks to perceive the mining environment through, for example, environmental monitoring (e.g., of the air and seismic background) to detect and predict risks and hazards. An online array of air chemistry and particulate sensors can provide a live stream of data that can be used to detect changes in atmospheric methane, carbon dioxide and degassing products of fracturing rocks, include fine particulates. Data analytics such as artificial intelligence-based anomaly detection are highly appropriate for this purpose (e.g., Zimek and Schubert, 2017). Seismic sensor networks could be used to image the fracturing process ahead of mining stopes, using extraction-induced noise as an active seismic source. Similar micro-seismic monitoring techniques are already in use in the fracking and sequestration industries, to monitor and image reservoir changes that are induced by the injection process (e.g., Aminzadeh and Dasgupta, 2013; Rodvelt, 2014). We foresee that treatments for noisy seismic data, such as noise cancellation, beam forming or other advanced signal processing techniques, and optimising the speed of the imaging algorithm in dealing with large streams of data (e.g., via decimation, approximation and workload parallelisation) are key to successful deployment of advanced and online seismic monitoring (e.g., Song and Toksöz, 2011; Shi et al., 2019; Li et al., 2019). To stream, store and utilise sensor network data, and to manage operational activities in real time, a digital mine integration platform is inevitable.

Sensors can also enable in-situ and rapid estimation of resource grades by using trained models that relate in-mine observational and analytical data (e.g., through remote sensing) to resource potential (e.g., grades and uncertainty) (Daniels, 2015; Nwaila et al., 2019; Samson, 2019; Zhang et al., 2021c). Leveraging this type of technology, in principle, it should be possible to perform more accurate and timely grade control and in-situ assessments to drive rapid feedback between the tactical and operational levels. Particularly, it should be possible to be more precise with orebody delineation, block modelling and selective extraction. In addition, this type of technology can enable more effective material sorting, which can enhance all aspects related to resource grades, such as grade-to-mill control, stockpiling and pre-concentration and waste valorisation processes at latter stages of the extraction and processing pipeline.

For operational planning, the goal is to sequence extraction such that a combination of safety, profitability and control is maximised. For example, in complex underground mines, the solution to extraction or panel sequencing is dependent on the financial objective, panel availability, market conditions and geotechnical conditions (e.g., Nwaila et al., 2021). In this context, with the exception of trivial cases, a best sequence is difficult to obtain analytically, and suboptimal approaches are compromises of profitability and safety. Stochastic optimisation and swarm intelligence algorithms (Beni and Wang, 1993) may be suitable. In any case, the adoption of modern approaches such as digitalisation in mining may need to occur either within a risk-compartmentalised setting within the mining industry and/or in an external setting, such as academia or dry laboratories (Ghorbani et al., 2022).

5.2. Rock mechanic solutions in deep underground mines

In deep underground mines, accessing minerals usually requires sinking and digging a shaft, excavating tunnels from the shaft to the vicinity of the deposit, and developing mine tunnels inside a mineral deposit to prepare it for extraction. Other than mine excavation tunnels, vertical infrastructure is necessary to facilitate mineral transport (ore passes) and ventilation (ventilation shaft). These infrastructures are excavated inside rocks; therefore, considering rock situations before and after excavating the facilities can be useful for supporting them. As mining becomes deeper, the most significant impact of depth on rock mass are the increase in in-situ stress (rock pressure) and rock temperature. With increasing stress, rock mass behaviour changes and becomes more difficult to anticipate, which increases operational risks. Therefore, deep mining can result in additional rock mechanical/geomechanical challenges (Cai et al., 2004, 2006). Rock responses include damage near openings and brittle failure. The impacts of deep brittle failure during extraction are potentially high, such as mine instability and human injury and/or fatality. In general, sandstone, kimberlite, clay, shale, and other weak rock types display undesirable geomechanical behavior, such as over-consolidated clay (e.g., the Opalinus clay at Mt. Terri; Yong, 2007). If brittle rock failure is unanticipated and rock mass is highly stressed, support systems may fail. Consequently, a number of issues must be considered including rock fracturing around mining excavations, the support and control of the fractured rock, the design of mine infrastructure and extraction (stopping) systems (Wagner, 2019).

Typically, rock mechanic problems begin at about 1500 m below the surface of brittle rock mines, while for weak rock mines, they could begin at 750 m. Vertical stress increases linearly with depth, depending on the weight of upper levels. In contrast, horizontal stress exhibits a different pattern that mainly depends on the rock type. For example, at the Kiirunavaara mine, by increasing the mine depth, the horizontal stress becomes the major principal stress (Sjöberg et al., 2001). In this instance, horizontal static stress can help stabilize and clamp the separated blocks inside the host rock near the opening. In deep underground mines, inevitable stress concentration promotes fracturing around opening. The most important stability problem is related to dynamic conditions that can reduce stability and lead to fallouts or collapses. Designing a support system is critical to prepare a safe environment for miners, protect facilities and infrastructures, prevent disorder in the mining process, as well as rock fallout and rockburst. Forseeable aspects of a support system design should occur before mine planning to avoid the imposition of unfavorable rock pressure, which necessitates extensive and expensive support measures. For deep underground mines, the consideration of support systems should pay particular attention to seismic and dynamic loading events in the vicinity of the excavation. It is necessary to use a combination of complex support systems to solve both static and dynamic problems. One approach is yielding-support tending, which is designed from flexible boundary and surface supports, and is intended to prevent extension of fractures near the excavation (Kaiser et al., 1996). In deep underground mines, mining-induced seismicity potentially creates instabilities like rockbursts and fallouts. The magnitude of the seismic event depends on energy stored in the rock mass which varies between 10^5 to 10^9 j. For mines where this is an issue, a type of rock support system that can absorb the majority of released seismic energy should be considered. A detailed description and working principle of a system for stabilizing the surrounding rockmass is presented by He et al. (2014). As an example, a static rock support was applied first at the Kiirunavaara mine. However, as mining progressed deeper, seismic activity increased. The static rock support was unable to handle the deformations caused by seismic events, therefore a dynamic rock support was subsequently deployed (Krekula and Thesis, 2017). At the El Teniente deep underground mine (Chile), numerous rockburst and seismic events since 1976, especially from 1990 to 1992 ($\leq$4.0 Richter magnitude) lead to a halt in production for more than a year while the production plan was reconsidered (Brown, 2007). Measures adopted to reduce seismicity are all knowledge-based. Such measures included: (a) a reduction in the volume of ore extracted as to allow for additional column support; (b) uniformization of spatial and temporal rates of production; (c) a gradual increase in extraction rate; (d) a limitation on the extraction rate based on recent (2 weeks) seismic activity; (e) and the de-stressing of the extraction zone prior to its excavation by means of a pre-undercut (Rojas et al., 2000a, b).

Mining companies with deep underground mines already use mine-wide seismic monitoring systems to record seismic waves of various magnitudes. This system can be viewed as a data generation source, which provides valuable seismic data that can be analysed to monitor and guide extraction. A combination of techniques, such as near real-time data analysis, e.g., tomographic imaging (Aminzadeh and Dasgupta, 2013; Rodvelt, 2014) and predictive analytics can be used to predictively achieve mine safety (Nordström et al., 2020; Törnman, 2021). For mitigating stress concentration and reducing rockburst hazards, mining-induced energy variations in the rock mass should be minimised. Stress reduction techniques such as hydraulic fracturing in deep formations may be useful. This method is most notably employed in El Teniente in Chile which was experiencing numerous rockburst and seismic events since 1976 (Brown, 2007). There, the use of hydraulic fracturing significantly reduced mining-induced seismicity (Araneda et al., 2007).

However, hydraulic fracturing near excavation can create new fracture planes that promote propagation. In the presence of a joint system, a newly generated fracture plane could form new blocks (or boulders). Depending on the active stress conditions, the generated blocks could become unstable. Avoiding mining activity in the vicinity of major geological structures such as faults and dyke can reduce the hazards of fault activation or slip and shear movement (Gay et al., 1984). Surface subsidence can also result from underground mining, which can be significant depending on mine size, orebody shape, mining excavation method and mine depth. In general, mining-induced surface subsidence becomes less problematic with increasing mining depth. Instead, probably the key impact of deep mining on surface structures is mining-induced seismicity, which can cause damages.

5.3. *Resource mapping, prediction, modelling and new approaches*

Traditional resource modelling makes use of orebody exploration data, which are derived from the analysis of drill core samples from the surface downwards. The cost of the sampling of deep orebodies and therefore resource estimation is clearly more than that of shallower ones. A complicating issue has been that traditional geostatistics is a mature field after 60 years of refinement and is not experiencing substantial improvements today. Therefore, the tools of resource estimation are unspecific to the higher levels of risk and impact in deep mines (McKinley and Atkinson, 2020). It is unclear if traditional geostatistics would be sufficient to create trustworthy resource models in deeper environments. A first-principles deduction would suggest that if deeper orebodies are potentially more complex, then their spatial resource variability would be also complex. However, whether deep orebodies are generally more complex is unknown because the correlation between generally deeper mines and more complex orebodies is confounded and statistically weak presently. Nevertheless, if this would be the case, it could weaken larger-scale spatial correlations and therefore lower the reliability of geostatistical resource models. For deep mines, it is impractical to substantially increase the sampling resolution to compensate for increased spatial variability for resource modelling. Speculatively, there may be differences between deeper and shallower deposits that are yet to be generalised and thus, the long-term suitability of traditional geostatistics remains to be determined through practice. In any case, other solutions would likely become competitive following the rapid development in machine learning and artificial intelligence (McKinley and Atkinson, 2020).

One solution is to integrate in-situ grade estimation and prediction during extraction. Essentially, this entails a dynamic refinement of resource models and grade control on a per-panel basis by using in-situ grade estimations in a timely manner at the mining front. All microanalytical, remote sensing and geophysical methods that are capable of assessing geological, chemical and geophysical properties of mining panels are potentially suitable (e.g., Kaplan and Topal, 2020). For example, photon beam-based methods can be used to assess mineral and metal contents of exposed panels by analysing and applying predictive models to their reflection spectrum. For this purpose, technologies may need to be adapted to fit the in-mine environment and an appropriate digital integration platform would be necessary as derived information may be inferential rather than direct (e.g., geochemistry via machine learning). A successful deployment of in-situ estimation would permit grade-based feedback without costly and time-consuming chemical assays, which enables live sequencing, grade control and downstream processing with better granularity.

In the long term, to increase resource model reliability, it is likely that relationships beyond spatial correlations would become essential. Although co-kriging is already capable of utilising low-dimensional correlations between two or more measured quantities, it does not generalise well to an arbitrary number of dimensions, non-quantitative information (e.g., categorical) and complex relationships. If resource modelling, like prospecting or exploration, would become increasingly dependent on scientific hypotheses/models with a quantitatively predictive power, then data that describes orebodies would likely be mixed quantitative-qualitative (e.g., geology and geochemistry) and multidisciplinary. For such data, the ideal approach to modelling is data-driven predictive modelling, such as through machine learning, which is capable of identifying and leveraging complex, multi-dimensional patterns to make inferences. This approach has no counterpart in traditional geostatistics and its application to resource modelling could reveal a range of possibilities, such as rapid point-wise target prediction (e.g., Nwaila et al., 2019; Zhang et al., 2021c). The overall aim is to leverage abundant data and modern algorithms to increase resource model reliability.

A final challenge with the application of traditional resource modelling to deep underground mining is the ability to adequately assess resource uncertainty. In the deep underground environment, financial costs are higher, which is a persistent disadvantage, since any advantage gained in deep underground mines may be valuable to shallow underground mines. Therefore, the financial disadvantage must be compensated by an increase in certainty to mitigate the cumulative impacts of resource model uncertainty. Uncertainty analysis would likely have to be more reliable than that of traditional methods applied to shallow underground mines to mitigate higher financial costs of inaccurate resource modelling. Traditional geostatistical tools such as conditional simulations are likely to stay. However, similar techniques from the domain of machine learning and artificial intelligence may yield more reliable solutions. For instance, these techniques can leverage the variability of the geology inside mining panels to infer resource uncertainty (Kaplan and Topal, 2020), or use Generative Adversarial Networks to construct high-dimensional realisations of a resource model in a manner that is similar to, but more general and capable than conditional simulations (Zhang et al., 2021a).

Modern approaches to challenges in resource estimation, such as artificial intelligence should not be overstated. It is dangerous to expect that breakthroughs would be transformative, absolute and sustaining. In geostatistics, resource estimation makes use of models that were refined over 60 years (McKinley and Atkinson, 2020), while artificial intelligence, by virtue of its trans-disciplinary nature, is less model dependent and generally requires more data. Underlying assumptions of geostatistics (e.g., quasi-stationarity) are well studied and the entire process pipeline from sampling to model verification have much knowledge to offer to modern approaches using data-driven methods (McKinley and Atkinson, 2020). Hybridisation of data-driven methods with discipline-specific practices require substantial interdisciplinary research and requires time to produce sustained benefits to resource estimation. The data requirement for analytics is a superset of that of geostatistics and is technology-dependent, and therefore it is a standalone challenge that needs to be addressed. Unfortunately, a general knowledge of the data requirements and predictive analytics technologies for resource estimation is absent and current research remains academic. A sound approach to future deep-mining challenges would likely come from a combination of rigorous introspections of legacy and present mining practices and challenges, and timely but risk-compartmentalised interdisciplinary innovation and experimentation.

5.4. Value of legacy data in underground mining

Without industry-relevant data and a realistic research and development context, the digital and technological industrial revolution occurs along a steep slope. This is the key reason for why legacy data is of tremendous value. Legacy data is data that is not managed or governed using modern practices. However, for practical deployment of either transitional or affordable technologies in existing underground mines, it is important to demonstrate value, integration potential and cost effectiveness. The journey from initial consideration, proof-of-concept, proof-of-value to adoption is long but constitutes almost half of the roadmap to a dominantly automated context (Global Mining Guidelines Group, 2019). The history of mining is extensive, and particularly in South Africa where underground mining has generated enormous amounts of irreplaceable data (e.g., Manzi et al., 2015; Westgate et al., 2020; Zhang et al., 2021b; Nwaila et al., 2022). However, legacy data can be difficult to comprehend, as metadata, reference data and other supplementary information are incomplete, missing or not machine readable. Additionally, the data is of variable quality, dimensionality, coverage and coverage rate. This is a product of geoscientific evolution, as data generation methods changed over the history of resource exploration and extraction. Nonetheless, such issues may be remediated using a combination of modern data science and discipline-specific practices (e.g., Nwaila et al., 2019; Zhang et al., 2021b, c; Mutshafa et al., 2022). The benefits of legacy data cannot be understated. Primarily, the three key benefits of legacy data are: (a) its enormous intrinsic value; (b) its ability to bridge the present and the future; (c) and engineering data and sensors that are fit-for-future purposes.

Legacy data that describes exhausted or nearly exhausted deposits provide the last-known information regarding Earth's deposits of those types, and intrinsically, this data has irreplaceable scientific, engineering and historical value. In addition, digital- and data-driven insights that are derived from legacy data provide a competitive advantage for deep underground mining. Scientists routinely discover new insights from legacy data that ranges from characterisation, prediction and hypothesis testing of deep geological structures to geometallurgical properties of various ores (e.g., Cowan, 2020; Mutshafa et al., 2022). From an engineering perspective, legacy data has been successfully used to create machine learning algorithms that are highly specific to currently relevant data (e.g., Wu and Zhou, 1993; Jafrasteh et al., 2018; Zhao and Niu, 2020). Therefore, legacy data lowers the cost of technological adoption. Another key benefit of legacy data is that it is aggregated and paints a larger-scaled picture of extraction operations, scientific and engineering aspects. This is an advantage to legacy data that by virtue of our exhaustion of many deposits, will be difficult to rival (Ghorbani et al., 2020). In this regard, scientific discoveries that can guide the extractive process, such as detection and characterisation of geological structures, which is a serious issue in some deep mines (Manzi et al., 2015; Rodriguez-Galiano et al., 2015) can only be efficaciously derived from legacy data.

In a modern data-centric environment, data must exhibit various qualities that allow the data to be understood by predominantly people with extensive training in data science (Ghorbani et al., 2022). To transition towards such a future, studies of legacy data in terms of its structure, lineage, intelligibility, etc. to understand its fitness for modern data analytics are important to evolve existing mining processes and practices. In this regard, legacy data hold tremendous value to many disciplines since they expose the historical and current data management practices, and any transition towards a modernised data management would require a thorough understanding of the nature and application of legacy data.

Another valuable application of legacy data is to examine the efficacy of scientific reduction in our characterisation of mineral deposits. In the last several decades, the trend to understanding mineral deposits has been increasing levels of reduction, for example, moving from bulk geochemistry towards isotope and chemical maps of mineral grains (e.g., Itano et al., 2020; Lindsay et al., 2021). The emphasis on scientific reduction may not be needed for many mining needs and instead, system-level knowledge, potentially such as multiple-scale causality can be generated by methods that gather more but less detailed data (Kleinhans et al., 2010). Although the mismatch between scientific redction and system-level uses of data (e.g., machine learning and artificial intelligence) seems to be under-appreciated, the proliferation of remote sensing and portable X-ray fluorescence devices suggests that a shift in scientific philosophy is in progress. Since mineral deposits are complex systems, they exhibit intrinsic variability at every observational scale, and therefore, increasing levels of reduction is not always warranted for scientific purposes (Kleinhans et al., 2010). Legacy data contains a range of reductions, e.g., at the outcrop scale to isotopic scale. By studying legacy data, it is possible to conduct cost-benefit analyses and develop better data for modern uses. For example, for the purpose of local mapping, it may be possible to use machine learning to leverage high-dimensional relationships in bulk geochemical data using cheaper data generation methods to produce maps that are higher in quality than with current methods, because the cost per sample could be lowered in exchange for higher coverage rate. These types of trade-offs must be re-examined to optimise future practices in light of disruptive advances in computers and algorithms.

6. Summary and outlook

Human needs will continue to drive our desire to prospect, explore and mine natural resources. As desirable resources become depleted in familiar environments, we are forced to look for them elsewhere. Within the supply and demand system of non-renewable natural resources, the transition towards mining deeper mineral deposits is a natural progression to ensure an adequate supply of raw materials. This review paper summarised key drivers and challenges for deep underground mining and presents relevant scientific and technological innovations that are likely to be beneficial. Key drivers for a move towards deep underground mining include shallow resource depletion and to a lesser extent, environmental concerns. Within the deep mining environment, the main challenges include: environmental and geomechanical conditions; financial issues such as increased exploration and operational costs; and, geological issues such as the presence of deep geological structures that interfere with mining operation. Modern innovations that are most likely to benefit deep underground mining include: (a) integration of mineral processing and mining; (b) control measures for rock deformation, rockburst and inrush of mixed coal-gas and water; (c) and leveraging modern tools, mainly digital and automated mining, environmental intelligence perception and platform-level integration. To enable this transition, risk-compartmentalised interdisciplinary innovation, experimentation and legacy data will be key. Despite new approaches and advantages, it is important not to lose the importance of fundamental research and knowledge generation, since it is intrinsically human to understand nature and mining benefits mankind beyond merely resource production.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

- All authors agree with the submission.
- The manuscript is original and solely submitted to this journal
- The figures can be printed in black and white colour.

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Yousef Ghorbani: Conceptualisation, Funding, Iinvestigation and writing – original draft. **Glen T. Nwaila:** Conceptualisation, Funding, Investigation and writing – original draft. **Steven E. Zhang:** Conceptualisation, investigation and writing – original draft. **Julie E. Bourdeau:** Visualisation, writing– original draft. **Manuel Cánovas:** Writing– review and editing. **Javier Arzua:** Writing– review and editing. **Nooraddin Nikadat:** Writing– review and editing.

Declaration of competing interest

The authors declare that they have no known competing or financial interests or personal relationships that could have appeared to influence the work reported in this review paper.

Data availability

No data was used for the research described in the article.

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